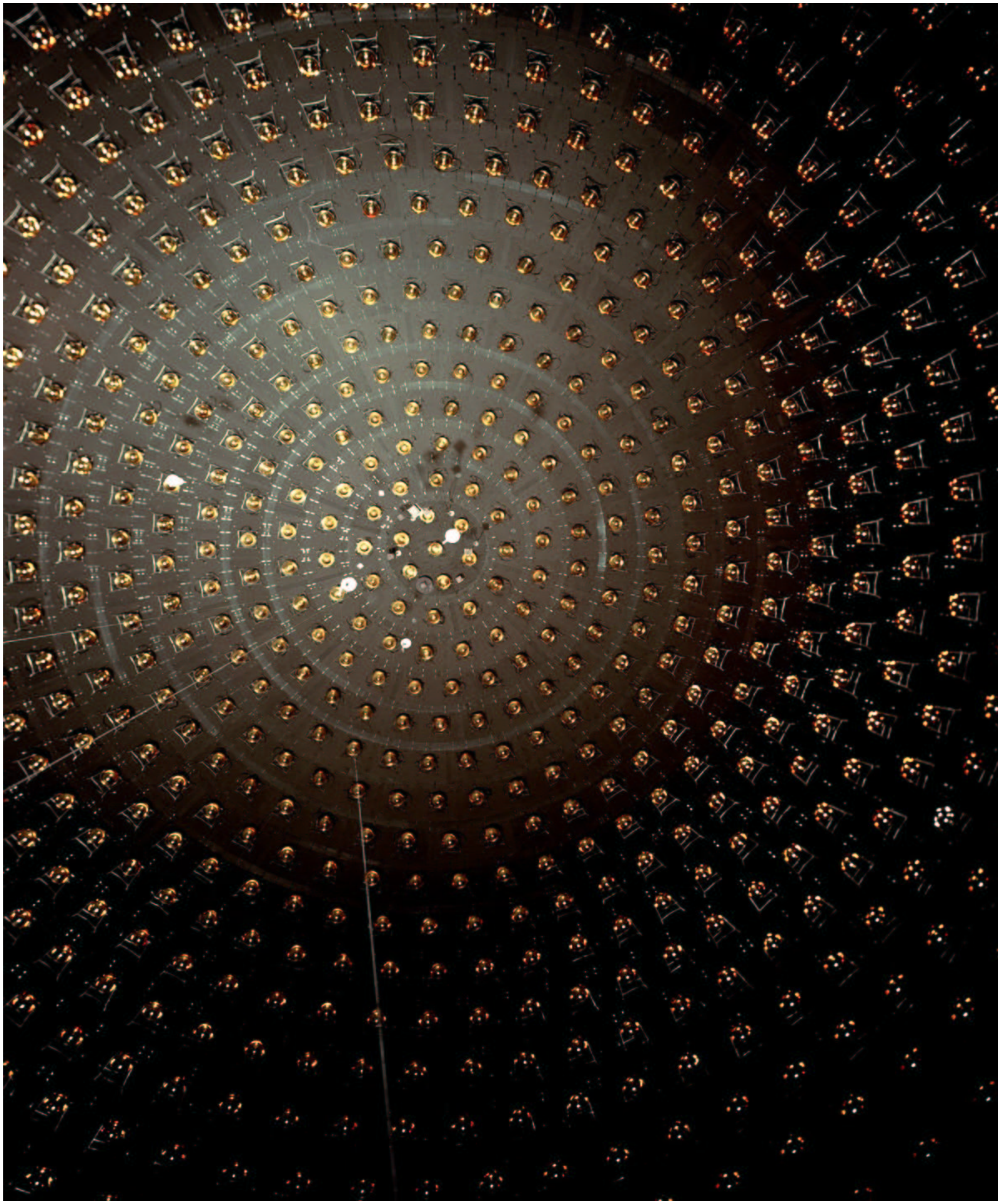


1+1+1 = 4 ?*

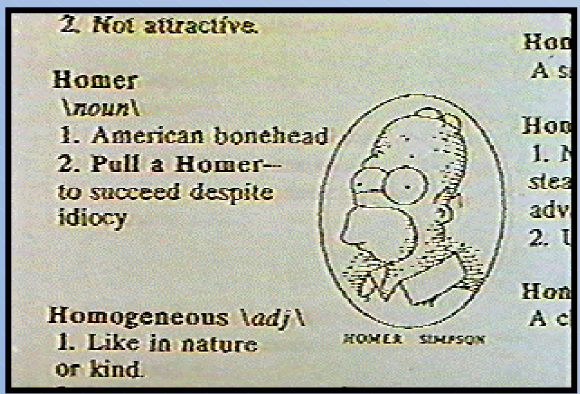
*(for larger values of 1)

Masses, Mixings, and Sterile Neutrinos

Joseph A. Formaggio
University of Washington

(My) Skill Level...

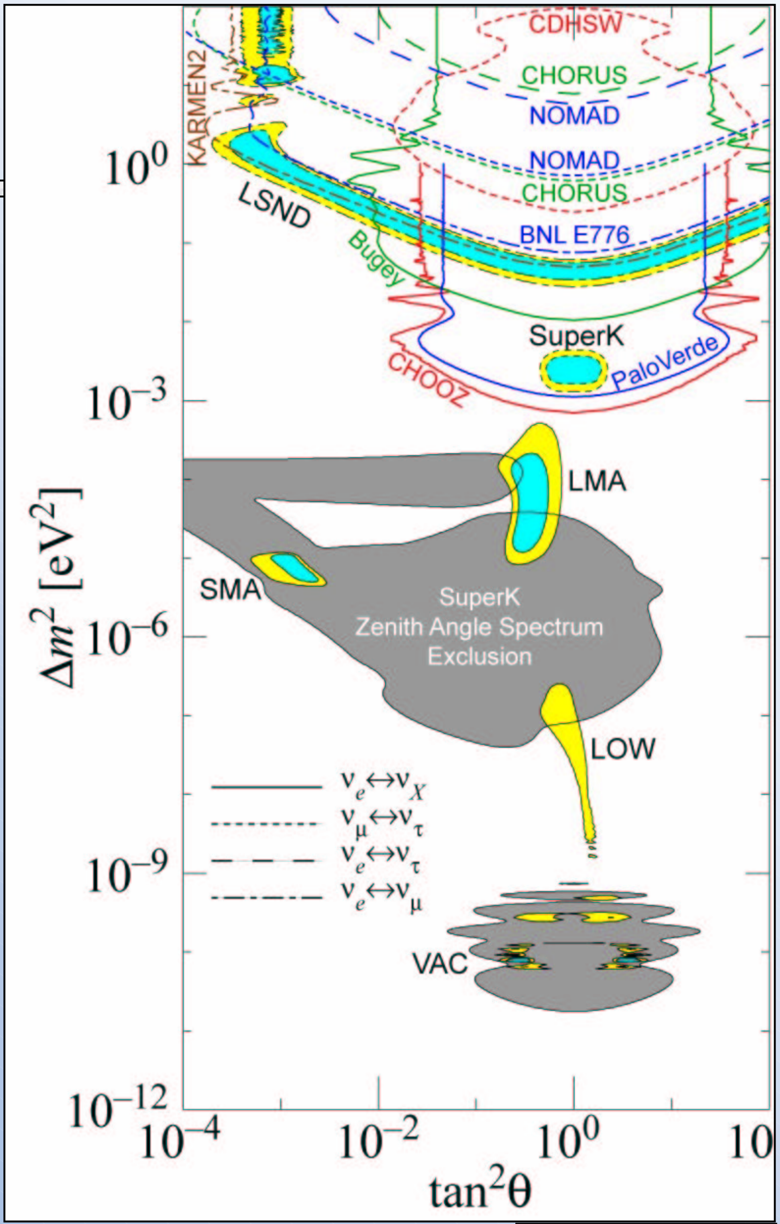
...Experiment



...Theory

Beyond a Reasonable Doubt…

- Our understanding of neutrinos has changed in light of new evidence:
- Neutrinos no longer massless particles (though mass is very small)
- Experimental evidence from three different phenomena:
    - Solar
    - Atmospheric
    - Accelerator
- Data supports the interpretation that neutrinos *oscillate*.



Murayama

The Standard Model

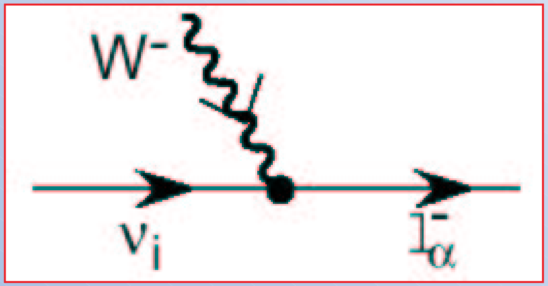
- Mirror to the quarks, leptons can be sub-divided into families…

Family:	1	2	3
Leptons	$\begin{pmatrix} e \\ \nu_e \end{pmatrix}_L$	$\begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix}_L$	$\begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}_L$
	$(e)_R$	$(\mu)_R$	$(\tau)_R$

- …which propagate via the exchange of the weak force

$$\mathrm{L}_{l\nu W} = \frac{-g}{\sqrt{2}} \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} \overline{l_{L\alpha}} \gamma^\lambda \mathbf{U}_{\alpha i} \nu_{Li} W_\lambda^- + \frac{-g}{\sqrt{2}} \sum_{\substack{\alpha=e,\mu,\tau \\ i=1,2,3}} \overline{\nu_{Li}} \gamma^\lambda U_{i\alpha}^\dagger l_{L\alpha} W_\lambda^+$$

- …and can be graphically be expressed as an exchange of W/Z bosons.



Mixing

- Just as in the quark sector, it is possible to define a *Lepton Mixing Matrix* (Maki-Nakagawa-Sakata-Pontecorvo)

MNSP Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Relates ν mass eigenstates to weak eigenstates

- For the Standard Model, there is no mixing...

$$U_{\alpha i} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrino Oscillations

If neutrinos have mass then the lepton mixing matrix (MNSP) is expressed as

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

and flavor eigenstates are a mixture of mass eigenstates.

Then

$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$$

and the state evolves with time or distance

$$\nu_e = U_{e1}e^{-iE_1 t}\nu_1 + U_{e2}e^{-iE\,2t}\nu_2 + U_{e3}e^{-iE_3 t}\nu_3$$

where $E_i^2 = p^2 + m_i^2$

$P_{e\mu} \sim \sin(2\theta)\ \sin^2(1.27\ \Delta m^2\ L\ /\ E)$

- Physics:

  Δm^2 & $\sin(2\theta)$

- Experiment:

  Distance (L) & Energy (E)

Steriles: Theoretical Motivation

- Unresolved Questions:
  - Why are neutrino masses so small?
  - Why are neutrinos seen only as left-handed particles? Is this compatible with neutrino mass at all?
  - Can neutrino mass tell us what is going on at a much higher energy scale?

φ_L only

- Sterile Neutrinos:
  - Can be invoked as right-handed partners to the neutrino
  - Naturally introduce mass into the (extended) SM and extend symmetry to quarks

$$\boxed{\mathcal{L} = m_D(\overline{\psi}_R\psi_L + \overline{\psi}_L\psi_R)}$$

  - Arise naturally from more comprehensive theories (Grand Unified Theories, etc.)

φ_L and φ_R

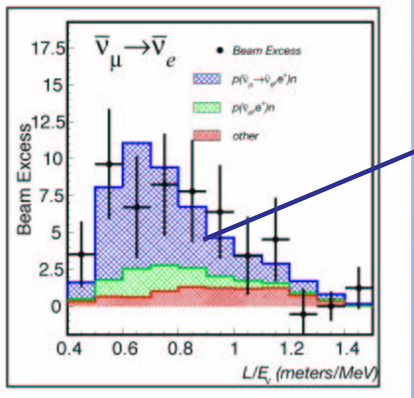
Beyond the Standard Model

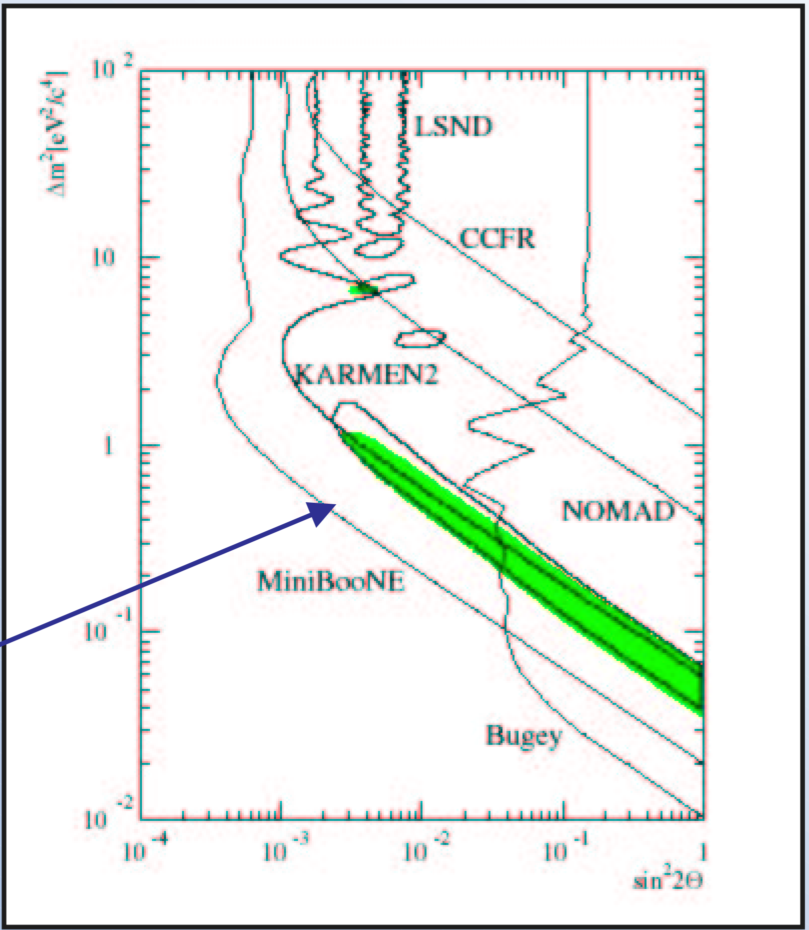
- It is possible to introduce heavy neutral leptons (“sterile” neutrinos) into the Standard Model
- Steriles exhibit certain properties in common with ordinary neutrinos:
  - Massive, potentially unstable
  - No electromagnetic couplings
  - No strong couplings
  - No direct weak couplings !
- No strong, no electromagnetic, no weak... no problem !

Steriles: Experimental Motivation

- LSND sees oscillation signal $\bar{\nu}_\mu$ to $\bar{\nu}_e$
- Combined analysis with KARMEN experiment consistent with $\Delta m^2 < 1$ eV^2

Oscillation Probability:
(0.264±0.067±0.045)%





E. Church, K. Eitel, G. Mills, M. Steidl
hep/ex 0203023

Doesn't Add Up

- If dealing with 3 neutrino species then…

$$\Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{31}^2 = 0$$

- But if Δm_{12}^2 and Δm_{23}^2 are both small then Δm_{31}^2 must be small as well (constrained).

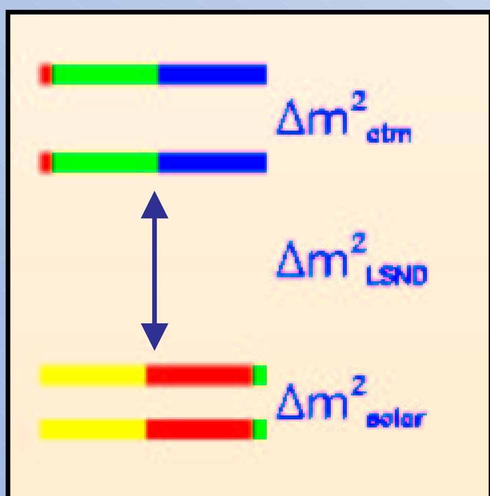
- …but this is not the case.

$$\Delta m_{solar}^2 = (4.0 - 9.0) \times 10^{-5}\ eV^2$$
$$\Delta m_{atm}^2 = (1.6 - 3.9) \times 10^{-3}\ eV^2$$
$$\Delta m_{LSND}^2 = (0.1 - 1.0) \times 10^{0}\ eV^2$$

- How do we constrain something we cannot see?

Two Phenomenological Models

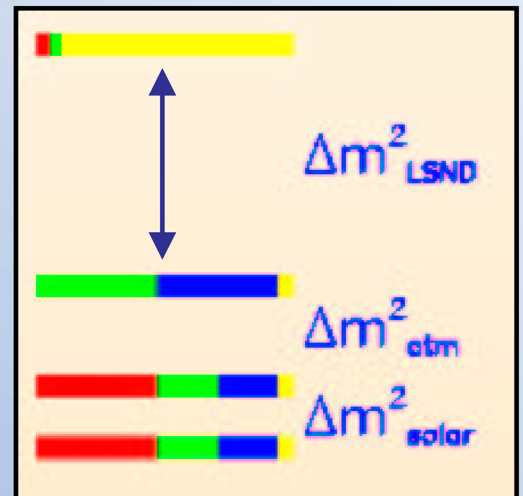
- 2+2 Model:
  - Assumes mass difference of LSND signal bridges between solar and atmospheric

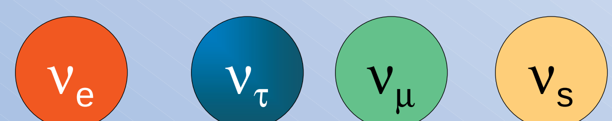


  - Model gives prediction of:

$$\boxed{P_{solar} + P_{atmo} = 1}$$

- 3+1 Model:
  - Assumes LSND mass apart from near degenerate weak states.





Testing the Sterile Content

- Using Solar & Reactor:
  - Direct measurement of ^8B flux from sun from SNO measurement
  - Use SNO + KamLAND to further constrain solar models
  - Use lowest energy solar ν's to understand steriles
- Global Fits:
  - Use combined fits to constrain 2+2 and 3+1 predictions
  - Determine if ν_μ to ν_τ really occurs
- "Direct" Measurement:
  - MiniBooNE

Sudbury Neutrino Observatory

2092 m to Surface (6010 m w.e.)

PMT Support Structure, 17.8 m
9456 20 cm PMTs
~55% coverage within 7 m

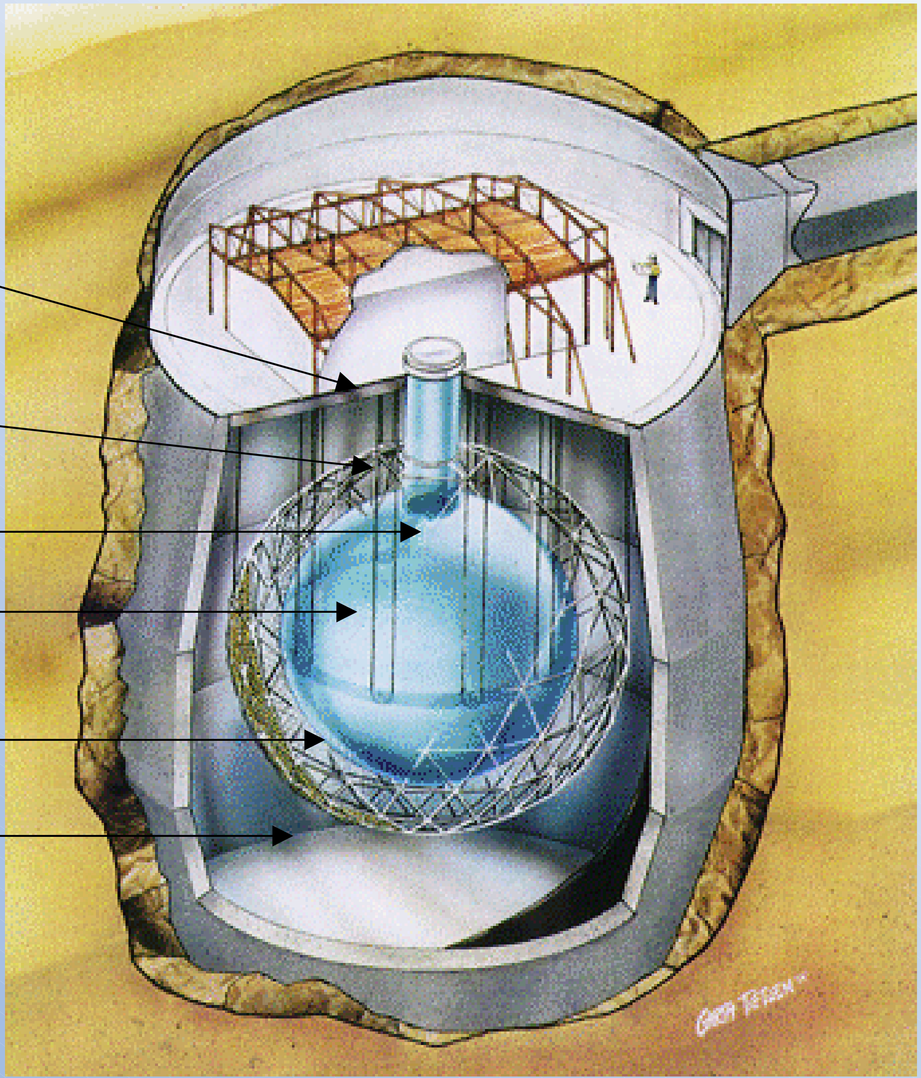
Acrylic Vessel, 12 m diameter

1000 Tonnes D_2O

1700 Tonnes H_2O, Inner Shield

5300 Tonnes H_2O, Outer Shield

Urylon Liner and Radon Seal



Unique Experiment

- Since only ν_e's are produced in the sun, ideal to measure the electron and non-electron solar flux in one single experiment.

Charged-Current (CC)
$\nu_e + d \rightarrow e^- + p + p$
$E_{thresh} = 1.4$ MeV

ν_e only
Signature: ^8B energy spectrum
Measurement of energy spectrum

Elastic Scattering (ES)
$\nu_x + e^- \rightarrow \nu_x + e^-$

ν_x, but enhanced for ν_e
Strong directional sensitivity

Neutral-Current (NC)
$\nu_x + d \rightarrow \nu_x + n + p$
$E_{thresh} = 2.2$ MeV

ν_x
Signature : mono-energetic γ
Measures total ^8B flux from Sun

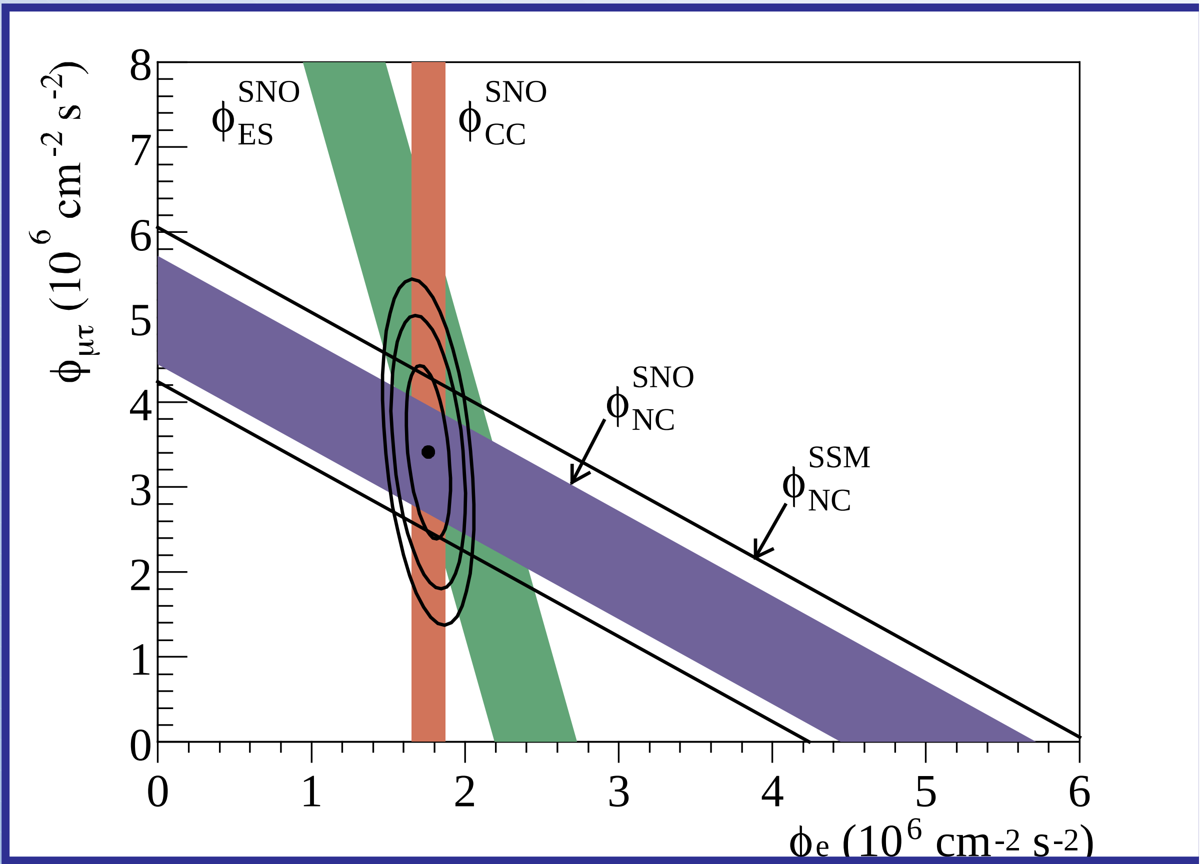
Solar Physicists Were Right!

- Measurement of ^{8}B flux from the sun.

- Final flux numbers:

$$\Phi^{8B}_{SSM}{}^{*} = 5.05 \;{}^{+1.01}_{-0.81}$$

$$\Phi^{NC}_{SNO}{}^{*} = 5.09 \;{}^{+0.44}_{-0.43}\;{}^{+0.46}_{-0.43}$$



* in units of 10^{6} cm^{-2} s^{-1}

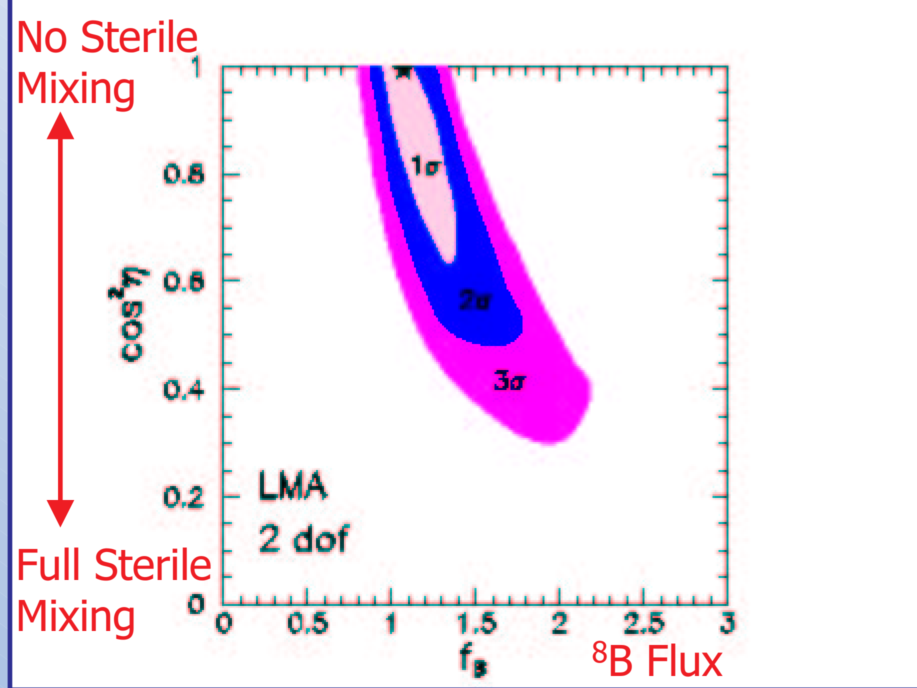
What About Sterile Neutrinos?

- Best fit favors no oscillations to sterile neutrinos
- Pure mixing $\nu_e \rightarrow \nu_s$ ruled out at the 5σ level
- Partial mixing (global fit) of mixing parameter to steriles (η):

$$\sin^2\eta < 0.70 \quad (3\sigma)$$

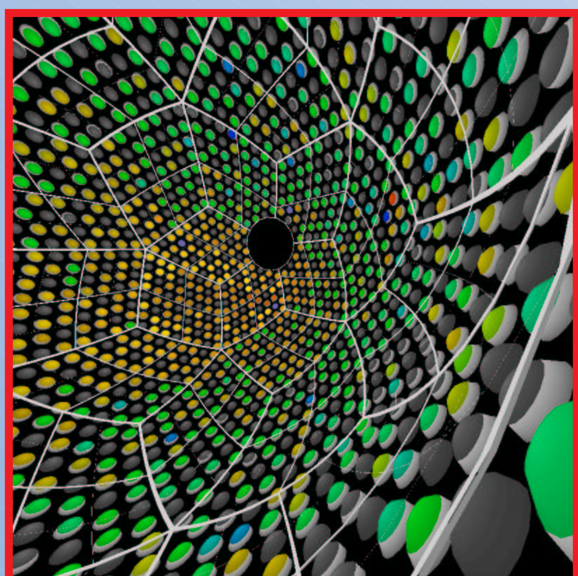
- What is the problem?
  - Sterile content driven by uncertainties in the flux. Is there a way to constrain it further?

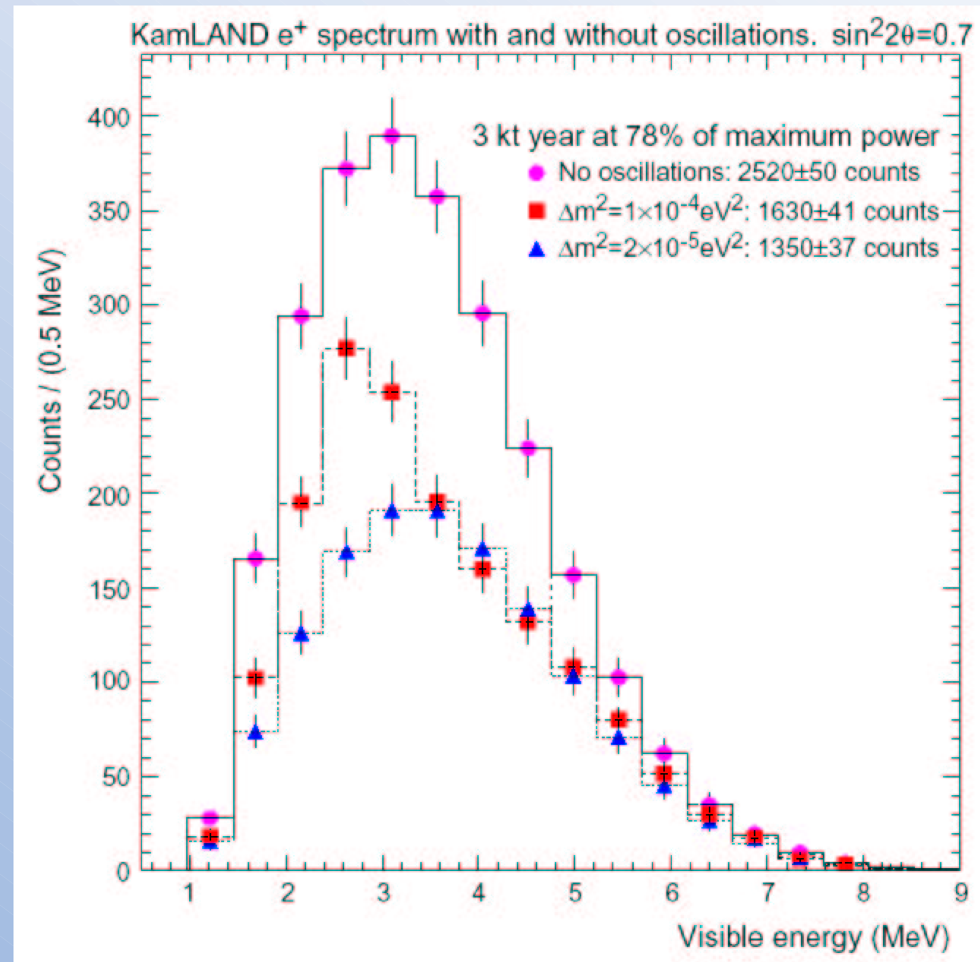
John N. Bahcall, M. C. Gonzalez-Garcia, C. Pena-Garay
hep/ph 0204194



KamLAND

KamLAND
Kamioka
Liquid scintillator
Anti-Neutrino
Detector





Combining KamLAND & SNO

- SNO provides an independent measure of the active content, but no constraint on the flux.
- KamLAND only reveals information about the mixing parameters, but not on the total active flux.
- Combining the two experiments provide an independent check on the active and sterile components

$$\boxed{\delta f_B = \underline{+}\ 12.5\%}$$

- If SNO improves NC measurement, this uncertainty will decrease even further
- Solar model independent.

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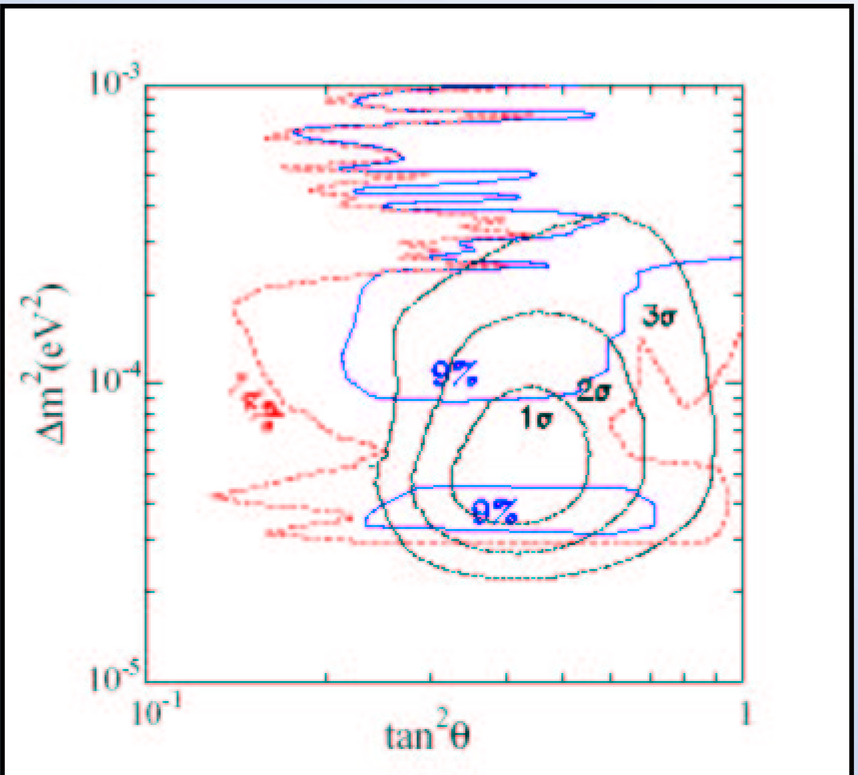
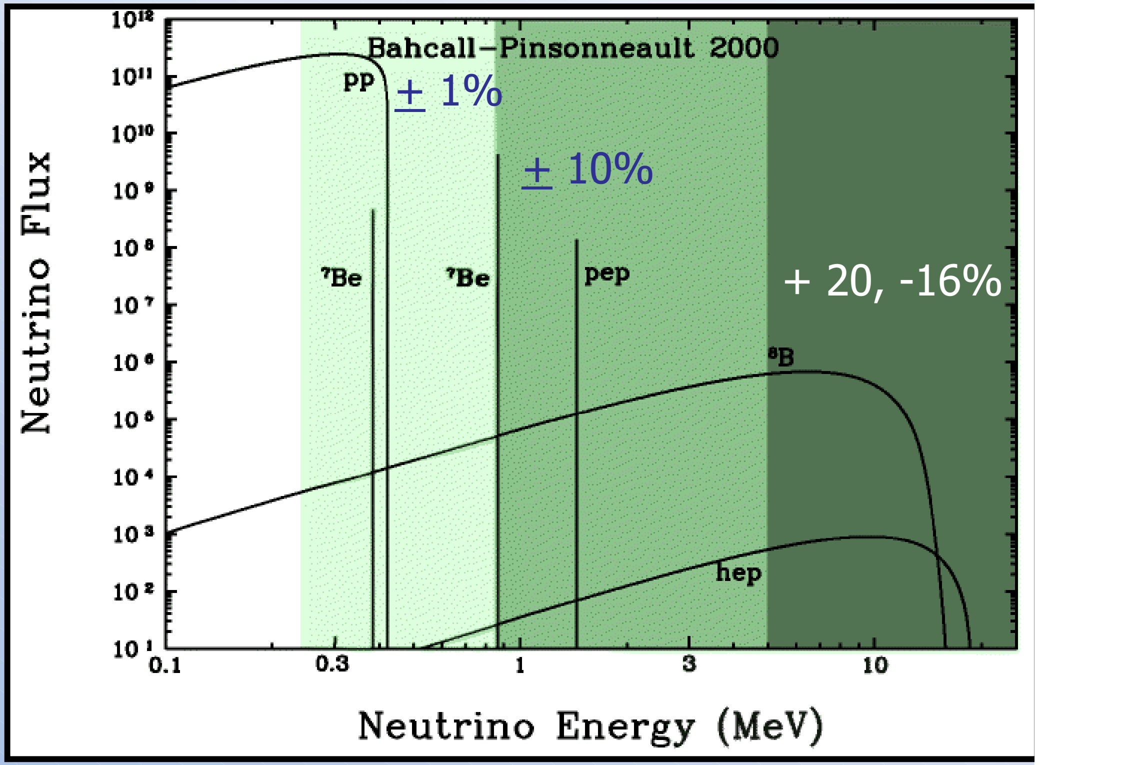
hep/ph 0204194



Precision Solar pp Measurements

- If one is able to access pp neutrinos from the sun, model is known extremely well.
- Limit there stems from detector uncertainties
- Need a dedicated experiment to probe this region and test both solar physics and steriles

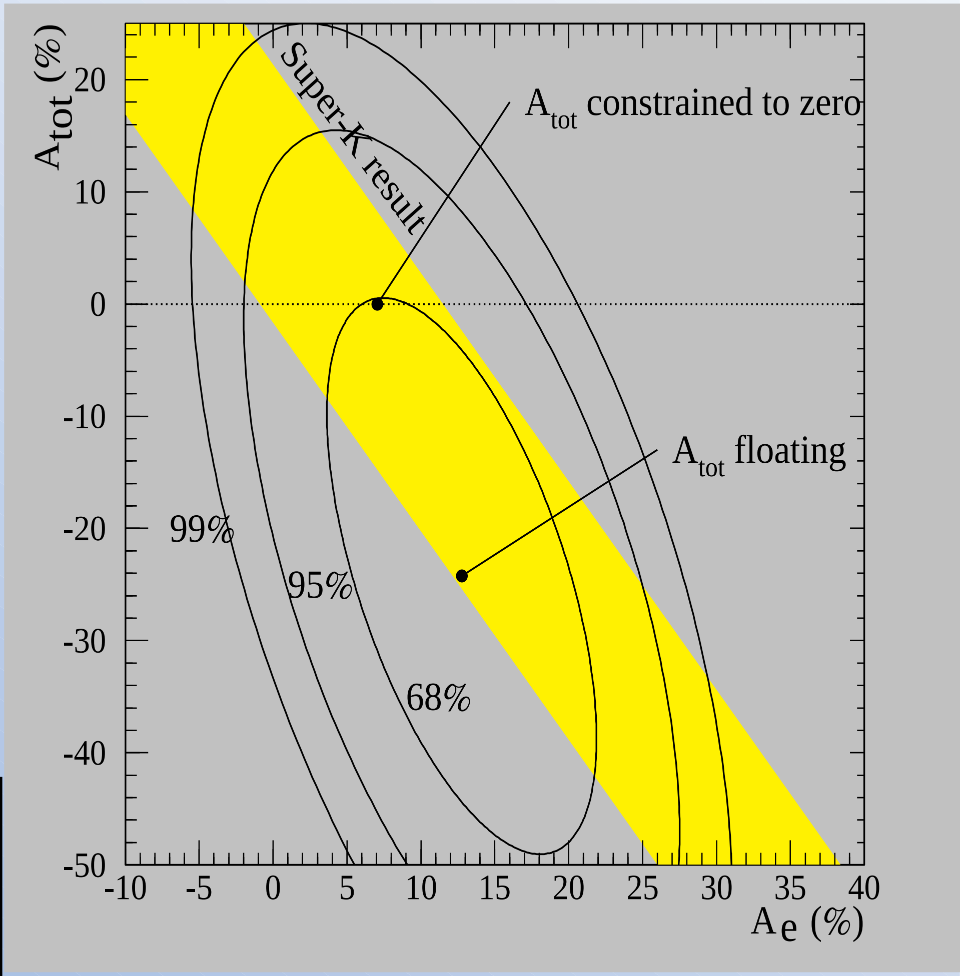


Day, Night, and Steriles?

- One can use day and night rates for neutral current rates in the sun in order to limit sterile neutrinos.
- Void of solar model systematic uncertainties
- Results consistent with no sterile content at 1.5 σ level.

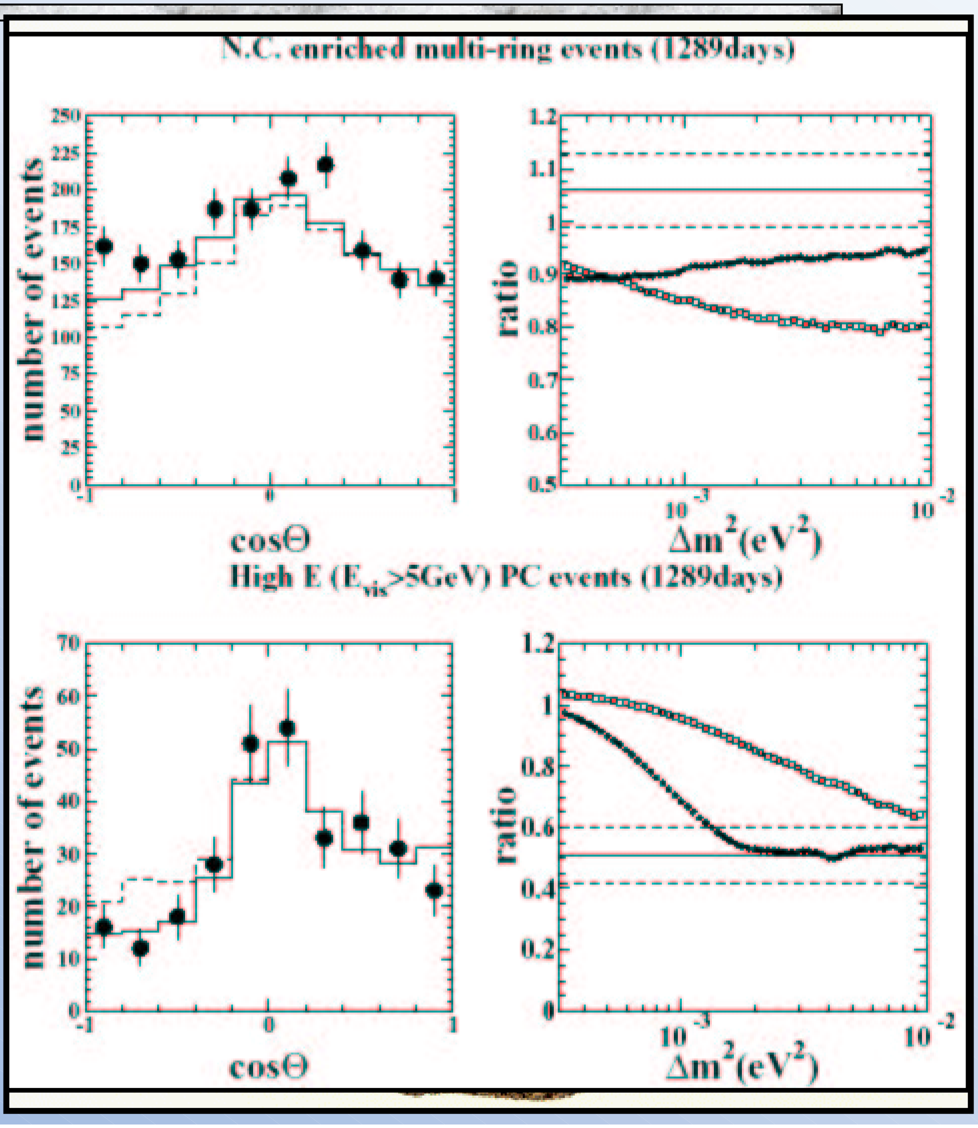
Signal Extraction in Φ_{CC}, Φ_{NC}, Φ_{ES}

$A^{SNO}_{CC} = 14.0 \pm 6.3$ %
$A^{SNO}_{NC} = -20.4 \pm 16.9$ %



Steriles with SK

- Also look at neutral current (active) portion of atmospheric neutrinos
- Look for deficit in neutral current (π^0 ring)
- Rule out pure mixing to steriles in favor of mixing to ν_τ

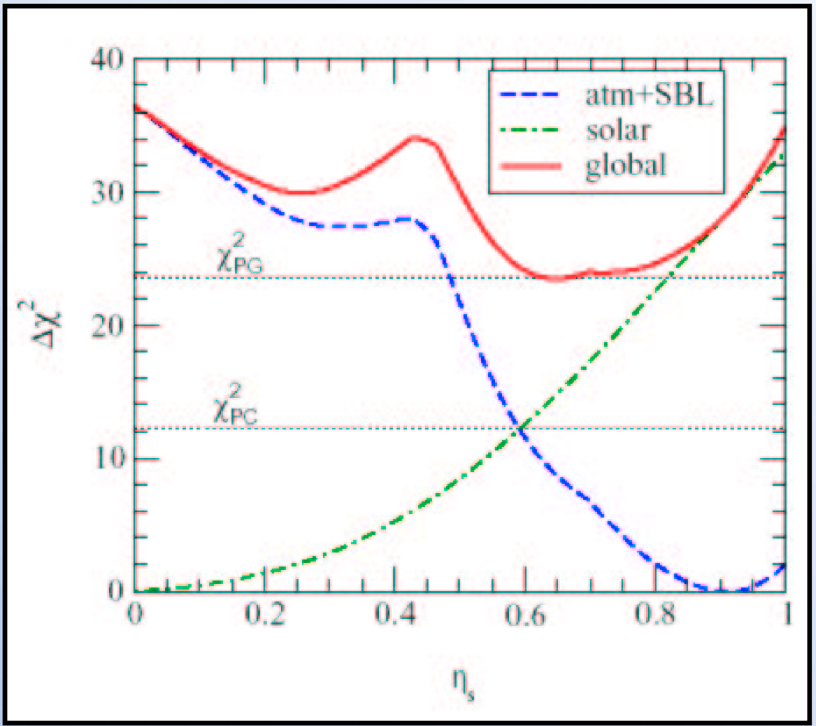


Do the Models Survive?

- 2+2 Model:
  - Model gives prediction for solar and atmospheric constraints

$$P_{solar} + P_{atmo} = 1$$

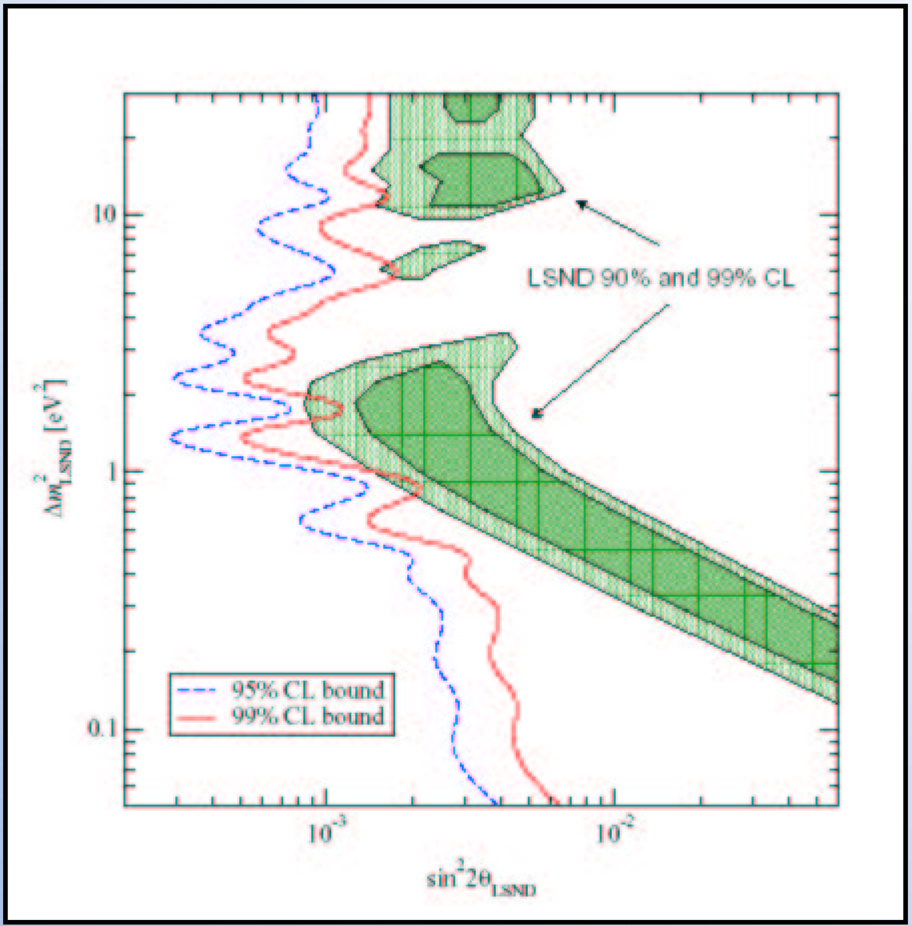
  - New data now available:
    - SNO's neutral current measurement
    - Recent data analysis from SK
    - Updated numbers from the LSND collaboration on oscillation parameters



M. Maltoni, T.Schwetz, M. Tortola, J. Valle
hep/ph 0209368

Do the Models Survive?

- 3+1 Model:
  - Model usually disfavored due to restrictions from reactor limits
  - New oscillation probability from LSND recent analysis places more favor on the 3+1 scheme
  - But be careful…
    - Treatment of assumptions and systematics
    - For excellent treatment of systematics, see Fogli et. Al.



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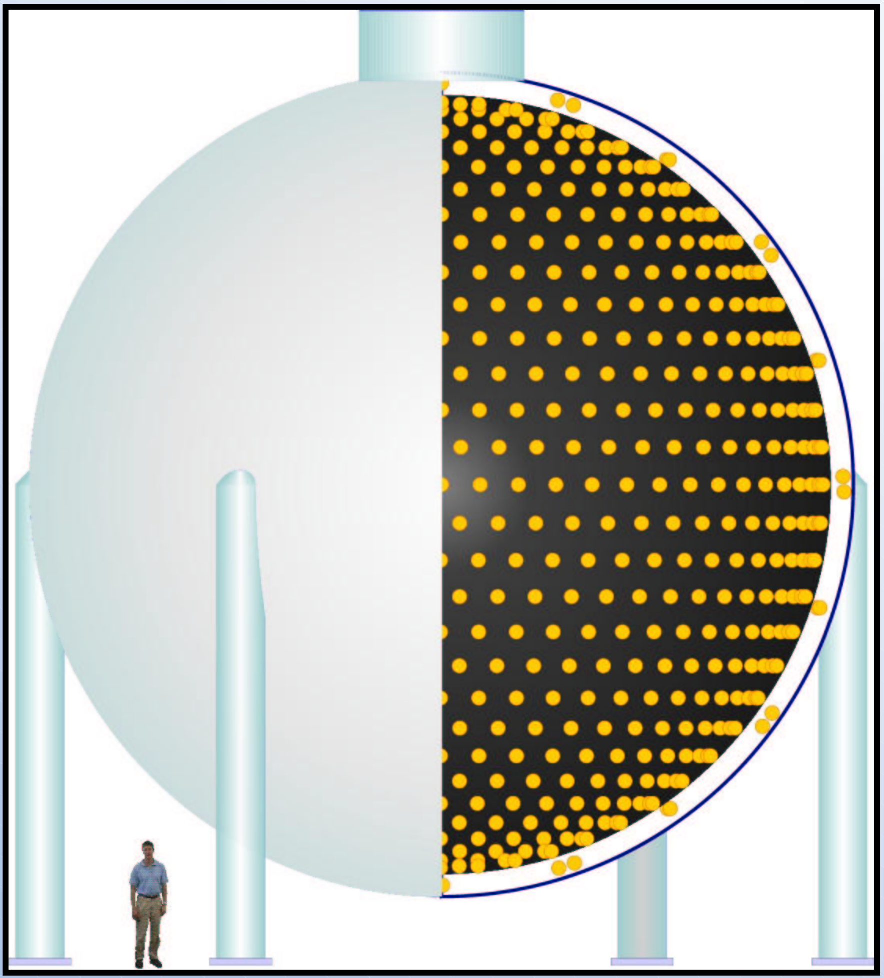
hep/ph 0209368

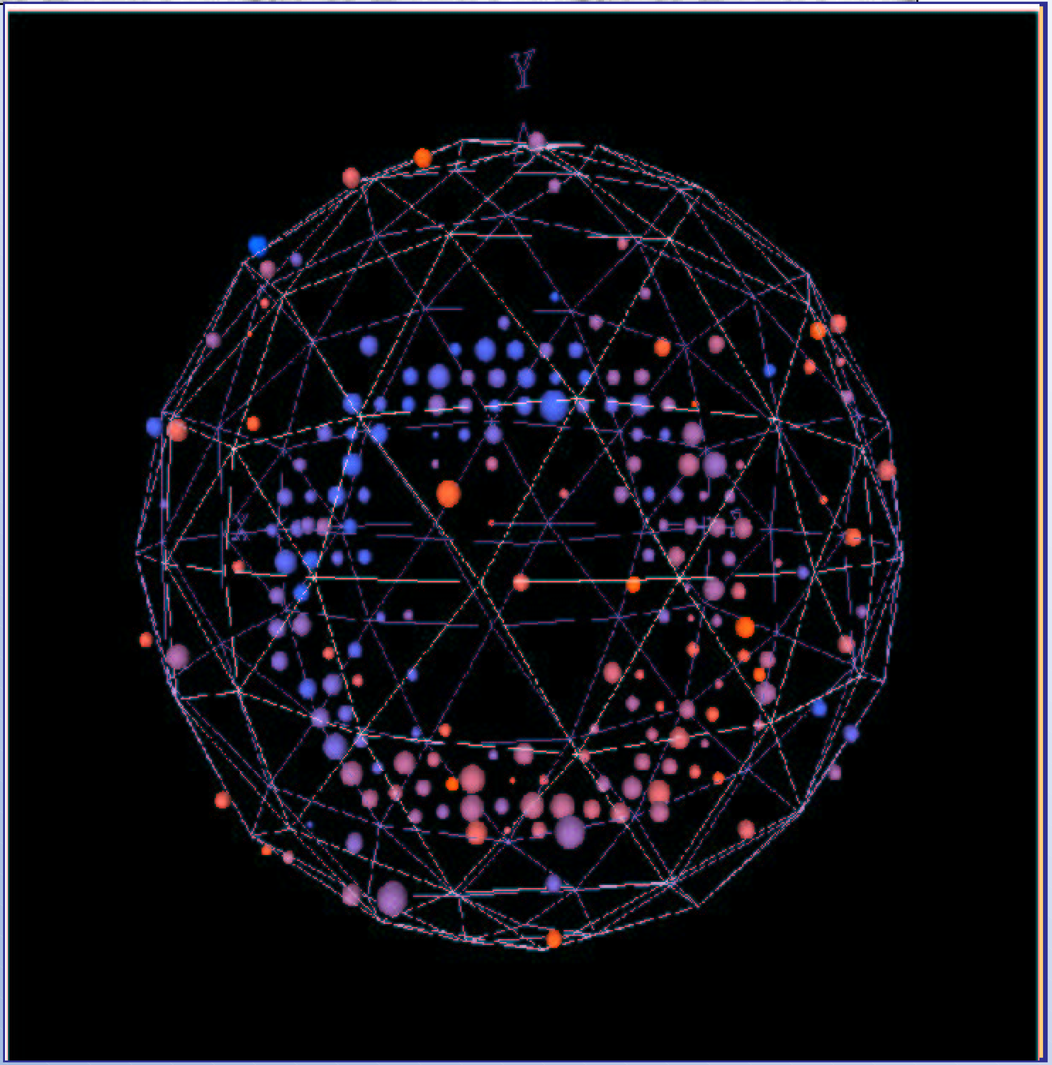
The MiniBooNE Experiment

- MiniBooNE experiment, in tradition with other oscillation experiments, is out to verify or refute the LSND signal
- Short baseline of ~1 GeV neutrino energy
- Probes same physics but with completely different systematics



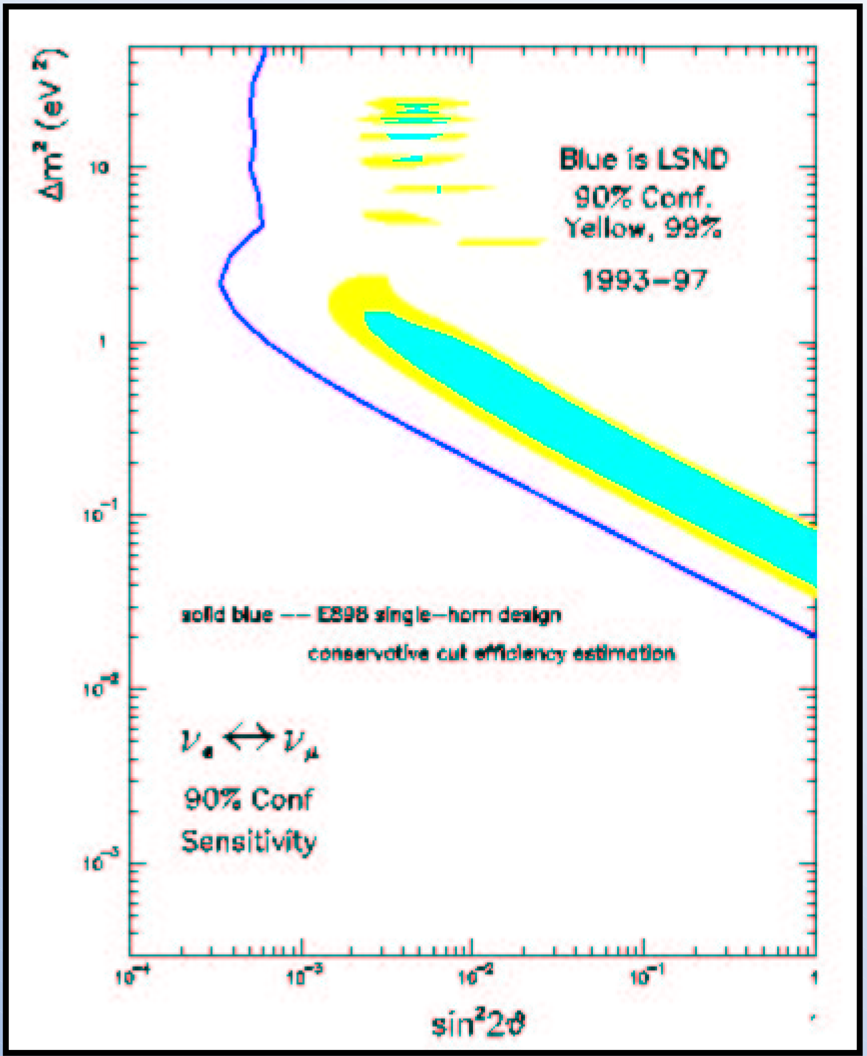
First Data

- MiniBooNE live and active
- First neutrino events from beam seen in detector
- Data taking for 1-2 years in neutrino and antineutrino modes



What to Expect

- If MiniBooNE sees a signal in neutrino running:
  - Confirmation of LSND
  - Is a single sterile compatible with rest of oscillation data?
- If MiniBooNE sees a signal only in anti-neutrino running:
  - CPT violation a reality?
  - What other systems test this scenario (KamLAND & SNO)?



- What to Conclude?

  - Steriles provide an attractive addition to the Standard Model

  - Experimental motivation from LSND provides a challenge to the framework

  - Independent checks using different systematics is key to confirming or probing sterile neutrinos

  - Exciting data from MiniBooNE and KamLAND to come!